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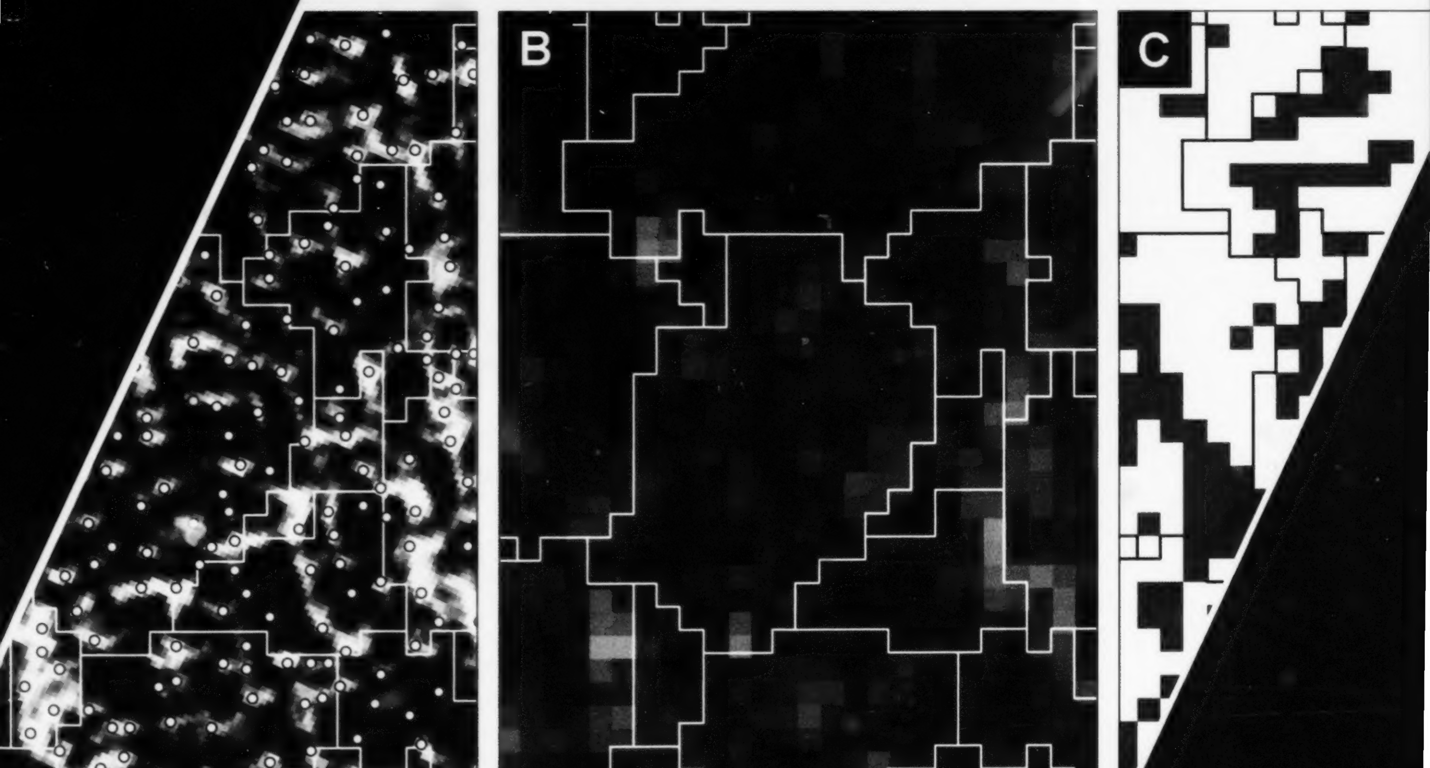

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Information need driven applications of remotely sensed data for mapping mountain pine beetle infestation at landscape and tree levels

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Contents

Abstract

When applying remotely sensed data, the information needs dictate the selection of data and analysis methods. Whether the scope of the application is over large areas or individual trees, a project typically must address logistical issues related to data selection and subsequent processing. Logistical issues include the scale at which the target must be measured (which will determine the appropriate sources of imagery), the attributes of interest, cost, timeliness, and repeatability. In this report, we present landscape-level and tree-level information needs and synthesize approaches for detection and mapping of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) red-attack damage with remotely sensed data, from a forest management and disturbance mitigation perspective. The goal of this communication is to provide the reader with an understanding of the nuances and realities of using remotely sensed data to fulfill a specific information need: from identifying the actual information need, selecting the image data and analysis methods, to producing desired outputs. Although demonstrated in the context of mountain pine beetle, many of the issues, considerations, and decision points raised here are applicable to other forest management and monitoring applications of remotely sensed data.

Résumé

Lorsque vous mettez en application des données de télédétection, ce sont les besoins en information qui déterminent la sélection des données et les méthodes d'analyse. Que la portée de l'application concerne de grandes zones ou des arbres en particulier, un projet doit généralement aborder les aspects logistiques relatifs à la sélection des données et au traitement qui en découle. Les aspects logistiques comprennent notamment l'échelle à laquelle la cible doit être évaluée (qui déterminera les sources appropriées de l'imagerie), les attributs en question, le coût, la survenue et la répétabilité de l'événement. Ce rapport présente les besoins en information à l'échelle du paysage et des arbres et synthétise les méthodes mises en œuvre pour détecter et cartographier les dommages au stade rouge causés par le dendroctone du pin ponderosa (*Dendroctonus ponderosae* Hopkins) à l'aide des données de télédétection, dans une perspective d'atténuation des perturbations et d'aménagement des forêts. Cette communication a pour but de de donner au lecteur toutes les clés nécessaires à une bonne compréhension des nuances et des réalités liées à l'utilisation de données de télédétection pour satisfaire des besoins en information spécifiques : de l'identification des besoins en information réels à la production des résultats visés en passant par la sélection des données d'image et des méthodes d'analyse. Même si c'est probant dans le cas du dendroctone du pin ponderosa, de nombreux éléments d'appréciation, questions et points de décision abordés ici sont similaires à ceux abordés dans d'autres applications des données de télédétection relatives à l'aménagement et au suivi de la santé des forêts.

Introduction

Remotely sensed data are a proven source of information for the detailed depiction of vegetation type (e.g., Gould 2000; Luther et al. 2006), structure (e.g., Gamon et al. 2004; Healey et al. 2006), and condition (e.g., Rossini et al. 2006; Wulder et al. 2006a). The spatial, spectral, and temporal resolutions of the sensor's data determine the manner in which vegetation may be characterized, and are key considerations that enable or preclude a given investigation. Thus, when undertaking applications with remotely sensed data, it is imperative to have a clear understanding of the information need that is to be satisfied, thereby allowing for the selection of the most appropriate imagery and analysis methods.

In this report, we address the range of issues associated with the use of remotely sensed data to satisfy two different information needs resulting from the same insect disturbance agent. The first information need is the characterization of mountain pine beetle red-attack damage over large areas, and to meet this need we apply remotely sensed data with a moderate spatial resolution. The second information need is the detection and characterization of tree-level mountain pine beetle attack damage, and to meet this need we apply high spatial resolution remotely sensed data. The context for each of these information needs in the current mountain pine beetle epidemic in British Columbia is discussed, background on existing operational survey methods used to detect and map red attack is provided, potential logistical issues are itemized, and image processing and analysis approaches are presented. The goal of this report is to impart sufficient background on the process of identifying the information need, selecting suitable imagery and appropriate analysis methods, and producing outputs, so that the reader has a greater appreciation of the mechanics of a project that uses remotely sensed data to fulfill a specific information need. Furthermore, the reader should gain an appreciation for how remotely sensed outputs augment existing survey methods, providing more comprehensive information for forest management.

Context: Mountain pine beetle outbreak

In western Canada, the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) population has reached epidemic levels, primarily in British Columbia, where the area of infested forest increased from approximately 164,000 ha in 1999 to 8.5 million ha in 2005 (Westfall 2006). At epidemic population levels, mountain pine beetles generally spread through mature stands and cause extensive mortality of large-diameter trees. Even though virtually all species of pine within the mountain pine beetle's range are suitable hosts (Furniss and Schenk 1969; Smith et al. 1981), lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) is considered the beetle's primary host. The biology of the mountain pine beetle is a complex and extensive subject and the reader is referred to a recent work by Safranyik and Wilson (2006) for further information.

There are two aspects of mountain pine beetle biology that may impact the selection of survey methods to characterize beetle damage: the first is a change in foliage colour of attacked trees, and the second is the size of the beetle population and the spatial configuration of the resulting damage. Mountain pine beetle attack manifests as a characteristic change in foliage colour. Immediately following a mass attack (i.e., concurrent attack by a large number of beetles, which overcomes the defences of a healthy tree), the foliage of trees remains visibly unchanged; however, a drop in sapwood moisture has been measured as a consequence of the attack (Reid 1961; Yamaoka et al. 1990). When the host tree is killed, but still has green foliage, it is in the green-attack stage. The first visible sign of impact is a change in foliage colour from green to greenish-yellow that usually begins in the top of the crown. These trees are referred to as faders. Generally, the foliage fades from green to yellow to red over the spring and summer of the year following an attack (Amman 1982; Henigman et al. 1999). The leaves gradually desiccate and the pigment molecules break down; initially the green chlorophyll pigment molecules are lost, then the yellow carotenes and red anthocyanins (Hill et al. 1967). Slowly, the needles drop until the tree is completely defoliated. Twelve months after being attacked, over 90% of the killed trees will have red needles (red attack). Three years after being attacked, most trees will have lost all needles (grey attack)

(British Columbia Ministry of Forests 1995). There is variability associated with the progression of attack stages as the rate at which the foliage will discolour varies by species and by site (Safranyik 2004).

Mountain pine beetle populations exist in one of four distinct states, representing the size and spatial configuration of the beetle population, and the resulting damage to the host species: endemic, incipient-epidemic, epidemic (e.g., outbreak), and post-epidemic (Safranyik 2004). The mountain pine beetle is endemic to the forests of British Columbia, and at this level, the beetle typically focuses on weakened hosts. For beetle populations to remain at this state, extreme mortality must occur within each generation of beetles. Incipient epidemic populations are those that can successfully mass attack a large-diameter host tree. Under favourable climatic conditions, and with abundant hosts available, infested spots will increase in size and coalesce to form larger patches of infestation, particularly in areas with extensive, contiguous regions of mature lodgepole pine. If these favourable conditions are sustained over long periods of time, epidemic population levels will result. Finally, when epidemic outbreaks collapse due to host depletion or sudden, severe low temperatures, beetle populations will continue in a post-epidemic state, with continuing population decline as a result of increased competition for suitable hosts or increased host resistance (Safranyik 2004).

Information needs

From a forest management perspective, estimates of the location and extent of mountain pine beetle red attack are critical; however, the precision required for these estimates varies according to the management objective under consideration (i.e., strategic, tactical, operational) and the nature of the infestation (i.e., endemic, incipient-epidemic, epidemic, and post-epidemic). The range of information requirements are matched by a hierarchy of different data sources that are currently used to map red-attack damage (e.g., aerial overview surveys, helicopter surveys, aerial photography, field surveys), with each data source offering a different level of detail on location and extent (Wulder et al. 2006b). Surveys designed to collect information regarding the location, size, and impact of mountain pine beetle populations may be conducted over large areas using satellite-based sensors or airborne platforms, or may be done at the individual tree level by ground crews. As a result, the extent of the survey may range from millions of hectares, to just a few hectares. Each survey method has limitations, with the collected data being applicable to different management situations.

Landscape level

Over large areas, information needs are often strategic, with information on the location, extent, and severity of the infestation being used to assess the resources required to address the infestation, and to prioritize the allocation of these resources to specific areas based on various criteria (e.g., severity of infestation or economic impact). In addition, strategic-level information on the intensity and spatial extent of the mountain pine beetle infestation is required for activities such as timber supply review, biodiversity conservation, forest inventory update, and land use planning (Wiart 2003).

A key component of strategic-level planning is the modeling of various management scenarios and treatment activities over a protracted timeframe, in order to determine the impact of management actions on the beetle population, spread of the beetle, and total wood volume (Powell et al. 2000; Eng et al. 2004). Such predictive models may be calibrated by baseline information characterizing the stands currently infested, or stands that have been infested in the past. Information on beetle impacts may be used to parameterize models and validate assumptions, or alternatively, support the backcasting of models by providing tangible data to reconstruct the history of the spread of a beetle infestation (within the limits of sensor lifespan). Over large areas, there is a need to account for the amount of area and forest that has been impacted by the beetle and discern a general trend in population levels over time (Wulder et al. 2006c).

Tree level

At the tree-level, surveys are often conducted to confirm trends in beetle population growth or decline and spread, as indicated by the coarser-scale surveys. However, ground surveys are the only reliable means to identify the green-attack stage and are therefore a necessity for any mitigation program (Wulder et al. 2006a). The ratio of green to red trees (G:R) is used to express the rate of population increase and is essential information for decision making regarding treatment options. Furthermore, ground surveys are often a regulatory requirement for designing a logging or sanitation plan (British Columbia Ministry of Forests 1995).

Current operational survey methods

Aerial overview surveys are often the most appropriate techniques for surveying large areas of mountain pine beetle damage due to the inherent speed and efficiency with which they can be completed. The aerial overview surveys, conducted visually by aircraft and on an annual basis, are designed to cover the maximum possible area, and provide general reconnaissance on trends in forest health at the provincial level. Most importantly, the information gathered in the aerial overview survey is made available for strategic planning within three months of the completion of the survey. The objective of the overview survey is to detect and delineate a wide variety of forest health concerns at map scales ranging from 1:100 000 to 1:250 000. To meet this objective, surveys are conducted using fixed-wing aircraft that fly at speeds of 150 to 170 km/hour, at altitudes ranging from 500 to 1000 m (British Columbia Ministry of Forests 2000). The aerial overview surveys provide sufficient information to characterize the general location of the damage, to approximate the gross area of damage, and to indicate the general trend in damage from one year to the next. However, the shortcomings of these overview surveys, which include large errors of omission when damage is light, a lack of rigorous positional accuracy, and the variability in estimates of attack magnitude, limit the utility of overview surveys directing operational activities (Aldrich et al. 1958; Wulder et al. 2006b). What these surveys do provide, however, especially for large jurisdictions with extensive tracts of managed forest (> 100,000 ha), is an initial stratification of the landscape that can direct the collection of more detailed infestation information with greater spatial accuracy.

To detect and map smaller and more concentrated areas of mountain pine beetle infestation, forest districts or licensees conduct more detailed aerial surveys. These surveys are normally completed at a scale of 1:20,000 using a helicopter with a Global Positioning System (GPS). A GPS position is taken at the centroid of an individual cluster of red-attack trees. The information collected from helicopter GPS surveys is used primarily for expediting the deployment of field crews to find green attack in areas where suppression activities are recommended. An advantage over other survey methods is the low error of commission; the surveyor gets a good look at each crown and can differentiate between bark beetle and other damage agents such as flooding, mechanical damage or porcupine girdling. The disadvantage is that there may be errors of omission if the coverage of the helicopter-GPS survey is not systematic across areas of lodgepole pine forests (Wulder et al. 2006b). Furthermore, although it is very effective for small and localized area surveys at the early stage of infestation, it is prohibitively expensive when dealing with a beetle outbreak over a large area.

Ground surveys vary in terms of the intensity, quality, and quantity of data collected, depending on the survey objective. These surveys generally take two forms — walkthroughs or probes. In British Columbia, guidelines for using the appropriate ground survey method are provided by the provincial government (British Columbia Ministry of Forests 1995). When the aerial overview survey indicates that an area is less than 5% red attack, walkthroughs are designed to delineate spatially discrete pockets of current (green) attack. Walkthroughs are unsystematic, reconnaissance-level surveys used to determine if more detailed surveys are required. If the aerial survey shows that an area is between 5% and 25% red attack, a full probe is conducted, provided the area is harvestable. Full probes are systematic strip surveys that collect very detailed information on stand conditions. The information gathered from the probes is

used for the purposes of designing logging and sanitation plans. Finally, if an area is determined to be more than 25% red attack, walkthroughs may be conducted to verify the status of the insect population (British Columbia Ministry of Forests 2000).

Logistical considerations

Once the information need is clearly identified, data and methodological options may then be considered. Several logistical issues may emerge when acquiring remotely sensed data to address a specific information need. These issues include the scale at which the target must be measured (e.g., landscape-level or tree-level damage), the attributes of interest (severity, spatial extent, green-to-red ratio), cost, timeliness, and repeatability. Some of these issues are more relevant for landscape-level applications that seek to map red-attack damage over large areas (e.g., cost, timeliness); however, some of these issues are biological and apply regardless of the survey method employed (e.g., timing of attack). Independent of the information need, there will also be applications-specific data requirements (see example in Figure 1). Many of the following logistical issues stem from the acquisition and processing of the required data sources. While focused on a specific application, these issues may be considered as generic for remote sensing applications of vegetation. Specific details on methods for the landscape-level and tree-level applications are provided in subsequent sections.

Required Data Checklist

Remotely Sensed Imagery

- 1 pre-infestation scene
- 1 post-infestation scene (preferably with 2 year lag)

Calibration and Validation Data

- Locations of know red attack damage (e.g. derived from helicopter GPS surveys or air photo interpretation)
- Locations of pine forest with no mountain pine beetle attack (e.g. information from ground based sources are preferred; however, image derived alternatives may be used in the absence of ground data)

Forest Data

- Forest inventory information
- Forest harvesting information

Figure 1. Required data checklist for red-attack mapping of mountain pine beetle.

Timing

Trees that are attacked by the beetle in one year will not typically fade from green to red until the growing season of the following year. The optimal time to capture this fade in foliage is during the summer months of July, August, and September of the year following attack. This is also the best time to collect remotely sensed imagery, since the sun angles are optimum during these months across most of Canada, and, as a result, the amount of shadow in the imagery is reduced. Due to the variability in foliage fade rates, a two-year image gap between images is recommended in order to capture all of the damage associated with a

single year's infestation. For example, if a stand was infested with the beetle in August, 2001, not all of the infested trees will have faded by the summer of 2002. An image collected in the summer of 2003 is preferred since the damage from the 2001 infestation will be more visible. Some trees, infested in 2002, will have faded by 2003 and also be captured in the image. These image acquisition characteristics often require compromise when images are being selected. Non-optimal seasons or years will have an impact on the nature and quality of information captured. Images collected late in the year (e.g., October) can have a lower dynamic range (particularly true at more northerly latitudes). This reduction in spectral variance reduces detectability and will likely result in more difficulty in identifying red attack, due to increased spectral overlap between red attack and non-attack classes. The image acquisition impacts become both spatial (where scene edges meet) and temporal (the actual time gap between images, in years and seasonal representation). Imagery acquired in another year is typically preferred over non-optimal season imagery for remote sensing mapping applications (Wulder et al. 2004a). The variance between attacked and non-attacked areas for these non-optimal seasons impacts the quality of mapping results and increases the processing time required.

Spatial extent

Many scenes or portions of scenes may require processing, depending on the size of the area and the information need. For example, if the information need requires characterization of the temporal change in beetle damage over a large spatial extent, at least two dates of imagery will be required to measure the change, and multiple images will likely be required to fully cover the area of interest. By necessity, the infilling of image areas obscured by clouds and shadows could further increase the number of scenes required to facilitate complete spatial coverage of the area (Homer et al. 1997). Moreover, if the information need requires a high level of detail, the number of images further increases, given that remotely sensed data with a higher spatial resolution typically have a smaller image extent. Multiple images present several image processing challenges such as edge effects, geometric co-registration, image radiometric normalization, phenological and annual differences, and data handling issues (e.g., disk space and organization).

Costs

The costs associated with the acquisition and processing of remotely sensed data are not insignificant. As previously discussed, landscape-level characterization of mountain pine beetle damage generally requires the use of multiple scenes, presenting numerous image processing challenges. Tree-level characterization necessitates the use of higher spatial resolution imagery, which is generally much more expensive to acquire than data with a lower spatial resolution. While data acquisition will undoubtedly represent the bulk of the costs, additional costs may be associated with ancillary data processing (e.g., for calibration and validation), data management, and image analysis.

Expertise

Expertise in processing different types and large volumes of remotely sensed and Geographic Information System (GIS) data is required. Processing of the ancillary data in the GIS environment is critical for generating image masks, and to facilitate the development of calibration and validation data sets. GIS skills are also required to ensure effective data management during and through to project completion. Remote sensing skills are required to ensure consistent processing of the imagery and perform the analysis (prior to the thresholding process). During the thresholding process user experience will reduce the time required for final threshold definition and validation steps.

Ancillary data

Ancillary data are required for calibration and validation of the analysis methods used to detect and map red-attack damage from the image data. Ideally, locations of known red-attack damage and areas

that are not attacked will be available from ground surveys, detailed aerial surveys, or large-scale aerial photography (aerial overview surveys are too coarse to provide any meaningful data for calibration and validation purposes). Information on non-attack locations is also necessary, as it is not possible to monitor for commission error (false-positives) without knowledge of where potential host trees are, yet were not attacked. Image processing techniques to define a non-attacked class for accuracy assessment purposes may inadvertently include some attacked trees or stressed trees. The heli-GPS data and the associated red-attack tree counts for each point provide an excellent and widely available source of calibration and validation data, especially when combined with the other available ancillary data (e.g., forest inventory) or supplemental image information (e.g., using reflectance values to create masks).

Ancillary data sources are also important for generating masks that will restrict the image analysis and aid in vetting the calibration and validation data points. The forest inventory is used to extract all forest stands that have a pine component, thereby identifying all areas of potential host species. This mask is used to constrain the variability in spectral response resulting from non-forest or other dissimilar vegetation cover. Additional information on harvesting that has occurred since the forest inventory was last updated may also be used to constrain the area of available host species. The use of masks enables the processing of pixels where there is real change related to mountain pine beetle attack through focusing on applicable areas and change transitions (avoiding class changes from forest to cloud or shadow). An image-extent mask may also be used to reduce the image processing requirements by not processing no-data areas that are typically produced through the rotation or translation associated with geometric correction. The masks also aid in the selection of points for calibration, and reduce false positives in the mapping of red-attack damage. The remaining points enable the interpretation of the results to be made under an assumption that the calibration and validation is not affected by extraneous conditions. See Rogan and Miller (2006) for a summary of considerations and opportunities for integrating spatial and remotely sensed data to meet applications needs.

Image resolutions and remote sensing of vegetation

Information generated from remotely sensed data can be characterized by the image spatial resolution (pixel size), spectral resolution (wavelength ranges utilized), temporal resolution (when and how often are images collected), and the radiometric resolution (the degree of differentiation within the dynamic range of the sensor) (Table 1). Of these, changes in the spatial resolution are often the most distinct, and can significantly alter the information content of the remotely sensed imagery, in particular for vegetation (Figure 2). Recent advances in the development of high-spatial-resolution satellites, combined with the widespread availability of digital camera and scanning technologies, and increasingly sophisticated computer processing techniques, have contributed to an increase in the use of high-spatial-resolution imagery to estimate traditional and non-traditional vegetation attributes (Wulder et al. 2004b). When utilizing high-resolution remote sensing imagery (defined here as a pixel less than 10 m by 10 m in size), the image pixel may still be larger than the objects of interest. The pixels may be considered small in a relative sense, but if the objects of interest are trees, multiple trees may still be found in individual pixels, precluding object-based analyses. Strahler et al. (1986) posit a scene model for understanding the information content of remotely sensed data whereby there are many objects per pixel (an L-res environment) or, conversely, many pixels per object (an H-res environment). In this model, it is the objects of interest that are important for defining the utility of a given spatial resolution for a selected application.

With increased spatial resolution comes added complexity in classification of the image into homogenous vegetation classes. While the increased textural information available in high-spatial-resolution image data allows for improved interpretation based on the shape and texture of ground features, the current techniques to process and analyze satellite image data, such as the use of standard vegetation indices or per-pixel based classifiers (e.g., maximum likelihood) may not be applicable to the additional information provided by high-spatial-resolution image data (Goetz et al. 2003). This is because

Table 1. Example instrument-related spatial resolution ranges and levels of plant recognition in to be expected across a range of image scales (after Wulder, 1998). Note, as a heuristic, low, medium, and high spatial resolution ranges may be considered as pixels sided > 1000 m, 1000 – 10 m, and < 10 m, respectively.

Type or Photo Scale	Approximate Range of Spatial Resolution (m)	General Level of Plant Discrimination
Low Resolution Satellite Images	1000 AVHRR 500 (MODIS)	Broad land cover patterns (regional to global mapping)
Medium Spatial Resolution Satellite Images	30 (Landsat) 20 (SPOT multispectral) 10 (SPOT panchromatic)	Separation of extensive masses of evergreen versus deciduous forests (stand level characteristics)
High Spatial Resolution Satellite images (i.e. IKONOS)	≤ 1 (panchromatic); ≤ 4 (multispectral)	Recognition of large individual trees and of broad vegetative types
Airborne Multispectral Scanners	> 0.3	Initial identification of large individual trees and stand level characteristics
Airborne Video	> 0.04	Identification of individual trees and large shrubs
Digital Frame Camera	> 0.04	Identification of individual trees and large shrubs
1:25,000 to 1:100,000	0.31 to 1.24*	Recognition of large individual trees and of broad vegetative types
1:10,000 to 1:25,000	0.12 to 0.31	Direct identification of major cover types and species occurring in pure stands
1:2,500 to 1:10,000	0.026 to 0.12	Identification of individual trees and large shrubs
1:500 to 1:2,500	0.001 to 0.026	Identification of individual range plants and grassland types

*based upon a typical aerial film and camera configuration utilizing a 150 mm lens

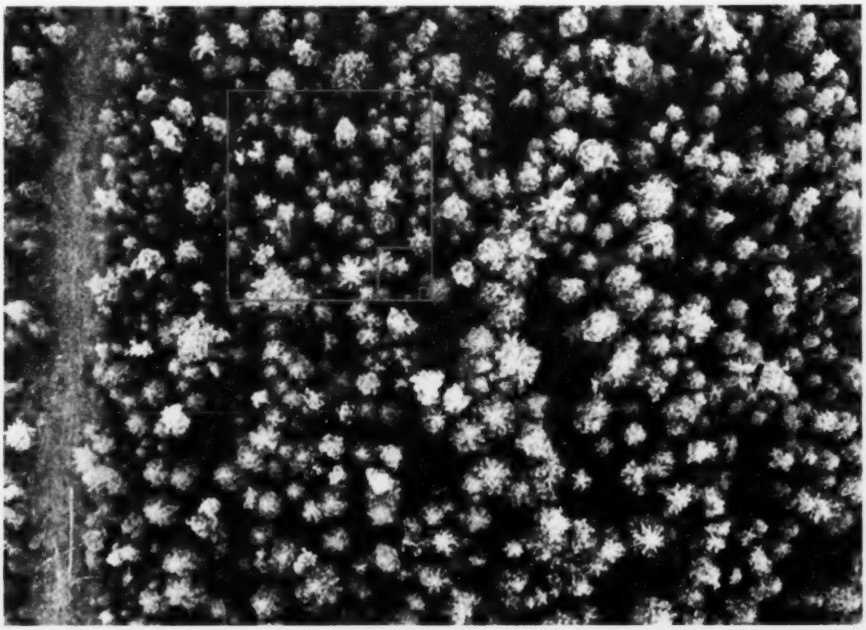

Figure 2. Change in image spatial resolution over a forested scene with crowns of varying condition. Superimposed pixel sizes range from 30 m (Landsat) to 4 m (IKONOS multispectral) to 1 m (IKONOS panchromatic).

the spectral variability of an individual tree (e.g., pixels representing sunlit crown, shaded crown, and the influence of factors such as branches, cones, and tree morphology) is more readily apparent on the high-spatial-resolution data, and this restricts the development of unique spectral signatures for tree or vegetation classification (Culvenor 2003).

The temporal resolution provides an indication of the time it takes for a sensor to return to the same location on the Earth's surface. The revisit time is a function of the satellite orbit, image footprint, and the capacity of the sensor to image off-nadir (e.g., not directly beneath the sensor, but at an angle). The timing of image acquisition should be linked to the target of interest. Some disturbance agents may have specific time periods (*e.g.*, fire, defoliating or phloem-feeding insects) during which imagery must be collected in order to capture the required information (Wulder et al. 2005), while other disturbances may be less specific (*e.g.*, harvest). For ongoing programs designed to monitor forest change before and after a disturbance event, the acquisition of images should occur in the same season over a series of years (known as anniversary dates). Anniversary dates are critical to ensure the spectral responses of the vegetation remain relatively consistent over successive years (Lunetta et al. 2004). The reduction in image radiometric quality for off-season imagery resulting from low sun angles and reduced illumination compromises the ability to capture changes clearly. Selection of scenes captured at the same time each year may reduce issues related to sun angle, shadow, and overall scene brightness. For some applications, the capacity to incorporate temporal resolution can be advantageous. For example, analysis of vegetation at both leaf-on and leaf-off times can provide important information on land cover, especially for seasonally variable vegetation such as deciduous species (Dymond et al. 2002). Temporal resolution of airborne sensors is flexible, with image collection undertaken on demand, often coincident with insect outbreaks or fires (Stone et al. 2001). There are often trade-offs between image spatial and temporal resolution that have implications for data selection. Generally, high-spatial-resolution imagery will have a greater temporal resolution due to the ability to angle the camera and acquire off-nadir imagery. Satellites such as IKONOS and QuickBird can image the same location on earth every 1 to 3.5 days depending on

the latitude of the target. Landsat, which is a medium-spatial-resolution satellite, revisits the same location once every 16 days.

Spectral resolution provides an indication of the number and the width of the spectral wavelength bands captured by a particular sensor. The spectral resolution of standard black-and-white aerial photography is known as panchromatic, and spans the complete visible portion of the electromagnetic spectrum, along with some portion of the near-infrared spectral wavelengths, with a single image band. Sensors with more bands of narrower spectral widths are described as having an increased spectral resolution. Currently, most operational remote sensing systems have a small number of broad spectral channels; for example, Landsat-7 Enhanced Thematic Mapper Plus (ETM+) data has seven spectral bands in the reflective portion of the electromagnetic spectrum and one band in the thermal-infrared region. Hyperspectral data (*e.g.*, instruments with more than 200 narrow spectral bands) are becoming more widely available (Vane and Goetz 1993) both on space-borne (such as the HYPERION sensor on the EO-1 platform) and airborne platforms such as HyMap (Cocks et al. 1998), *casi* (Anger et al. 1994), and the NASA Advanced Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Vane et al. 1993). The width and locations of these bands along the electromagnetic spectrum determine their suitability for forest disturbance applications. For example, a subtle spectral response, such as foliage discolouration, might manifest in a very particular part of the electromagnetic spectrum and may therefore be more effectively detected with a hyperspectral instrument, whereas a dramatic change, such as clearcutting, is discernable in a wide range of spectral wavelengths.

Detecting and mapping red-attack damage at the landscape-level

Information need

Over large areas, information on the location, extent, and severity of mountain pine beetle damage is required to determine the resources needed to address the infestation and to allocate those resources effectively. This information is also used for timber supply review, forest inventory update, biodiversity conservation, land use planning, and as baseline information to parameterize and validate the assumptions associated with predictive models. Landscape-level information is also used to direct the location and intensity of more detailed surveys designed to satisfy operational information needs.

Background

Remote sensing has been demonstrated as a useful technology for detecting and mapping mountain pine beetle red-attack damage (e.g., Skakun et al. 2003; White et al. 2005; Coops et al. 2006; Wulder et al. 2006c). Provided appropriate imagery is selected to coincide with the manifestation of the red attack, the damage can be mapped over large areas in an accurate and timely fashion using Landsat Thematic Mapper (TM) or ETM+ imagery and change detection methods (Skakun et al. 2003; Wulder et al. 2006c).

The infrared and short-wave infrared spectral channels of the Landsat sensor are known to be particularly sensitive to changes in forest structure (Hall et al. 2006). Image transformations that exploit changes over time in the infrared and short-wave infrared channels have been used to successfully map subtle forest changes related to insect disturbance (Price and Jakubauskas 1998) through to more extensive stand replacing disturbances such as harvests (Cohen et al. 1995; Wilson and Sader 2002) and burn severity (Epting et al. 2005). Single-date mapping of red attack is based upon the contrast between attacked stands and non-attacked stands. While reasonable classification accuracies may be found for single date mapping ($73.3\% \pm 6.7\%$, $p = 0.05$), issues with omission and commission error may emerge (Franklin et al. 2003). To address limitations related to mapping a change feature with single date imagery, multi-date change detection approaches were developed and applied.

Following are some examples in the literature highlighting the strength of approaches based upon the Enhanced Wetness Difference Index (EWDI) for mapping red-attack damage at the landscape level. Skakun et al. (2003) detected red-attack damage with an accuracy of 76% (± 12%, $p = 0.05$) for groups of 10 to 29 infested trees, and 81% (± 11%, $p = 0.05$) for groups of 30 to 50 infested trees. Wulder et al. (2006c) used the EWDI in conjunction with slope and elevation surfaces in a logistic regression approach to map red-attack damage in the Lolo National Forest in Montana, USA. The accuracy of red-attack detection was 86% (± 7%, $p = 0.05$). Using a similar process to that of Wulder et al. (2006c), Coops et al. (2006) mapped red-attack damage from a time-series of Landsat imagery with an accuracy of 69% (± 8%, $p = 0.05$) in an area with a relatively low level of infestation. The following section describes a detailed procedure for using multiple dates of Landsat imagery to identify the location and extent of mountain pine beetle red-attack damage at the landscape level. Approaches for optimizing Landsat scene selection, image pre-processing, image analysis, and accuracy assessment are also described.

Application example

As previously discussed, the creation of a large-area product detailing the location and spatial extent of red-attack damage involves the consideration of several logistical issues related to the mapping of a large area that are not often faced in small, research driven projects. Generating a consistent product over large areas involves the use of multiple scenes, collected on different dates and potentially in non-optimal seasons. In addition to issues such as data availability, the quality of available imagery can also be an issue. Imagery that is suitable for the detection and mapping of mountain pine beetle red-attack damage must be free of cloud and haze, and must be acquired during the biologically appropriate time period for mountain pine beetle (Wulder et al. 2006a).

EWDI approach to mapping red-attack damage

The EWDI has been effectively used to detect a range of forest disturbance types (Franklin et al. 2001, 2002, 2003, 2005; Skakun et al. 2003; Wulder et al. 2006c). The mapping approach developed to capture red-attack damage involves a sequence of steps including pre-planning, image scene selection, and image pre-processing, and analysis (Figure 3). The thoughtful selection of the study area is critical to ensure image acquisition costs are minimized. The EWDI approach performs best in areas with more homogeneous forest conditions and extensive areas of attack. Careful consideration should be made of those areas of the infestation where a spatially explicit mapping of red-attack damage will provide the greatest benefit to the end-user (e.g., areas with significant amounts of pine volume impacted by the beetle). The Landsat Worldwide Reference System (WRS) image database and aerial overview survey data provide an excellent planning tool for image selection, relating both spatial and temporal attribute conditions for the image locations. As outlined earlier, the selection of appropriate imagery is critical to the success of the EWDI mapping approach. Image selection criteria are constrained both by the aforementioned biological factors associated with the life cycle of the mountain pine beetle and physical attributes of the image resulting from the location of the area of interest. We recommend that scenes with excessive cloud and haze be avoided, and that any areas of cloud, cloud shadows, haze, topographic shadows, or snow cover that appear in the selected images be masked out.

Substantial effort is required to process all of the ancillary data sources necessary for the EWDI mapping approach. Masks must be generated from forest inventory and harvesting data to identify the area of suitable hosts. Calibration and validation data are important ancillary data sources. As discussed earlier, these data may come from purpose-acquired sources or from pre-existing surveys.

Geometric matching of overlapping scenes is a critical pre-processing step, even with orthorectified imagery, to ensure that that the images are properly co-registered. An image-to-image correction must be made between the two source images, using the older date as the control image and the newer date as the dependent image. Common permanent features (e.g., road intersections, landmarks) found in both of the images should be used for the registration. A second-order polynomial transformation and

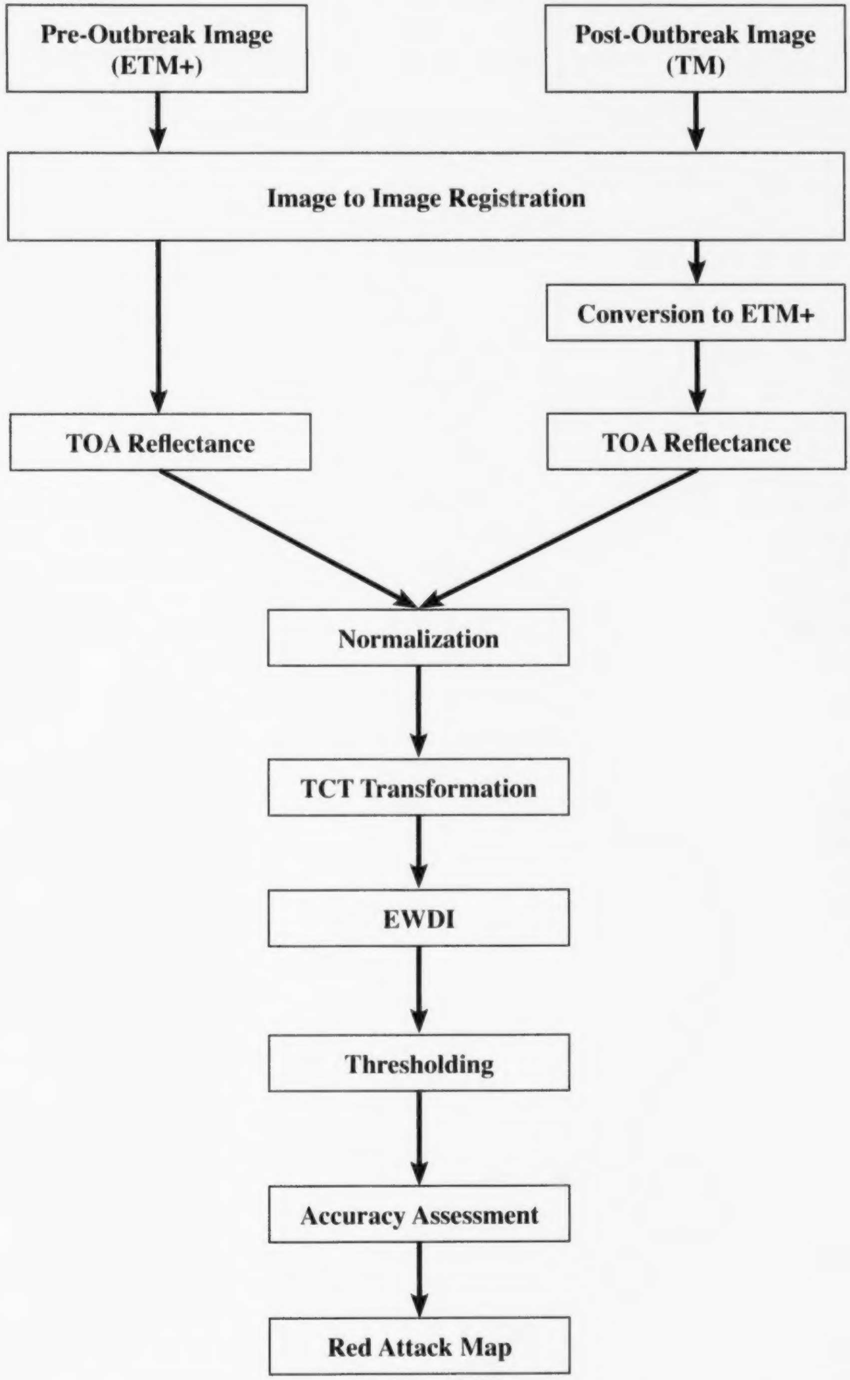

Figure 3. Summary of steps included in the processing flow to generate a map of mountain pine beetle red-attack damage from two dates of Landsat TM/ETM+ imagery.

nearest-neighbour resampling are recommended, along with a target root mean square (RMS) error of less than half a pixel. A minimum of 15 ground control points (GCPs), well distributed throughout the spatial extent of the image, are recommended. After the co-registration, quality assurance should be undertaken by displaying bands of the different image dates through different colour guns to capture and exaggerate offset effects.

Radiometric processing is the next required step. Radiometric correction makes the interpretation of the EWDI easier and increases the possibility of using standard values at the thresholding stage across the entire study area. Though the two Landsat sensors are compatible, they have different configurations (e.g., band centre wavelength, band width), spectral response, and signal-to-noise ratio (Irish 2000). To reduce the disparity between TM and ETM+ imagery, and to facilitate the application of the TCT coefficients developed by Huang et al. (2002a), the TM images are first converted to ETM+ at-sensor radiometry. The conversion is achieved by applying a set of gains and offsets to the TM images. Huang et al. (2002a) reported that pseudo-invariant objects can have different digital number (DN) values between summer and fall/winter. Much of the differences are removed by converting the DN to at-satellite reflectance. Huang et al. (2002b) developed a conversion algorithm to covert the raw DN to at-satellite reflectance for Landsat ETM+ data. Conversion of ETM+ DN numbers to top of atmosphere (TOA) reflectance is required to apply the Tasselled Cap Transformation (TCT) coefficients. Finally, images are normalized to remove the remaining discrepancies (snow, phenological differences, no data) between the two input images; the newer image date should always be normalized to the older image date. Image normalization reduces edge matching issues between adjacent images, but the quality of edge-matching should nevertheless be verified.

The TCT compresses spectral data into a reduced number of bands associated with physical scene characteristics (Crist and Cicone 1984). Though this transformation was originally constructed for agricultural applications, it has been used to reveal some key forest attributes (Cohen et al. 1995). In this procedure, the wetness indices of the TCT are calculated based on the two-date Landsat images. The coefficients for the TCT transformation are different, depending on the input image. The coefficients employed were derived by Huang et al. (2002a). The quality of the change detection process depends on the integrity of these image processing steps. Han et al. (2007) demonstrate an efficient protocol for integrating the radiometric processing, normalization, and the TCT calculation which reduces opportunities for error and substantially streamlines the processing effort.

Once the TCT wetness is generated for each image date, the EWDI is calculated with the following formula:

$$EWDI = W_1 - W_2 \qquad (1)$$

where W_1 and W_2 are the TCT wetness indices of image date 1 and 2, respectively. Generally speaking, large positive values indicate wetness loss, while small EWDI values show no change of wetness. Large negative EWDI values represent wetness gain. Therefore, the areas with large positive values in the EWDI image are likely to be the mountain pine beetle red-attacked areas (Skakun et al. 2003). However, mountain pine beetle red attack is not the only disturbance that results in a loss of wetness. Other forest management activities will all manifest as decreases in wetness. Figure 4 is a sample of a EWDI output; the white areas indicate areas of no change, blue indicates an increase in moisture, and red indicates a decrease in moisture.

The EWDI values of the attacked and non-attack pixels can be approximated by the Gaussian distribution, and can be separated by thresholding (Skakun et al. 2003). As shown in Figure 5, there are a range of EWDI values that can be linked to clearcuts, forest regeneration, and mountain pine beetle infestation. To determine the EWDI thresholds, calibration and validation data are required for both red-attack and non-attacked pine stands. The development of the EWDI thresholds is an iterative process. We suggest that the threshold values determined by Skakun et al. (2003) be used as a starting

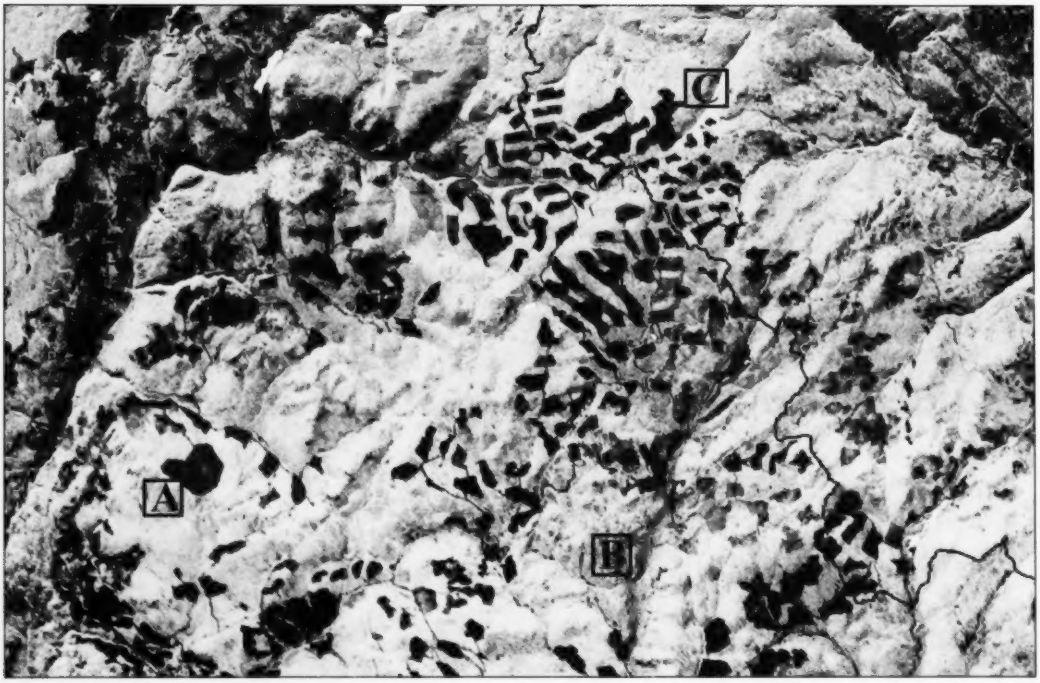

Figure 4. A sample of the EWDI from southern British Columbia. Red indicates a decrease in moisture from 2002 to 2004, blue indicates an increase in moisture, and white indicates no change. Point A shows a large moisture decrease in a clearcut area, B shows an area of mountain pine beetle infestation, and C shows a moisture increase due to regenerating vegetation in an old clearcut.

Figure 5. Generalized distributions capturing the EWDI values representative of red attack pixels (dashed line) and non-attack pixels (solid line). Thresholding is also illustrated, with a range of EWDI values categorized as red-attack.

point for threshold iteration. The threshold can then be varied (increased or decreased), using the calibration sets for non-attack and red-attack sites. The distribution of points for each of the non-attack and red-attack calibration points can be observed to decide where to place the thresholds. The intent in adjusting the threshold is to minimize commission error for red-attack detection, while at the same time maximizing the amount of red-attack damage that is accurately captured. Commission error is a particular consideration from an operational perspective as the deployment of field crews to sites falsely identified as red attack has greater consequence (in terms of time and costs) than sites where red-attack trees may not be identified (Wulder et al. 2006b). Once the threshold has been set, the accuracy of the output can be verified using the reserved validation data. Analysts need to maintain flexibility in values used in the thresholding. Previously used values can be used as a guide, but considerations such as imagery selected, geographic location, species mixtures, and site conditions can impact the values. The radiometric correction of the images is an attempt to make the changes required to the threshold values as slight as possible. Analysts can use previously defined thresholds as a guide for the mapping of subsequent imagery. Threshold performance (as assessed by measures of accuracy) needs to be balanced against total area mapped. Aerial overview survey data can serve as a useful indicator for development of threshold values, although users should expect the absolute values to be somewhat different (Wulder et al. 2006d). One-hundred percent of the area could be mapped as red attack to get a 100% true positive rate for red attack (indicating again the importance of a "non-attack" pixel validation dataset to inform on commission error).

The map products created with Landsat data should be subjected to an accuracy assessment. A transparent and robustly applied accuracy assessment provides a level of confidence to users of the map products. Specifically, an accuracy assessment provides information on the success of the detection methods used and identifies possible sources of error. It is also valuable for comparing and evaluating different mapping techniques and in the development of new methods. An error matrix is a useful mechanism for summarizing results and facilitating the calculation of accuracy measures; an error matrix enables a quantitative comparison of classes, or attributes, between independent validation data with the mapped results (Congalton and Green 1999). The comparison may be between the results of an analysis based upon remotely sensed data and field data, or between outcomes using different methodologies.

Measures of accuracy clearly depend on the quality and quantity of the validation data available. For example, the sites used to test the accuracy should not have been previously used in the classification process for calibration, or the accuracy assessment results may be erroneously high (Congalton and Green 1999). The size of the sampling unit should be in reference to the spatial resolution of the final product (Stehman and Czaplewski 1998). If the sampling unit is much smaller than the pixel size, it becomes unclear if the class that the pixel is identified as is due to the sampling unit being within the pixel or other pixel content. Furthermore, the sampling design should reflect the importance of different classes. If all classes are equally important then a stratified sample design could be applied, with the number of samples proportional to the area of each class. If one class is more important, then at least an equal number of samples should be taken in that class, even if it is rare on the landscape.

The research on the use of satellite imagery to map the red-attack stage of mountain pine beetle attack completed over the last 5 years has provided the foundation for recommending a red-attack mapping approach for large areas. The core method, generated from this research, is robust and produces useful map products. These map products may subsequently be processed to generate custom information layers in either raster or vector formats. The issues of major concern when detecting and mapping red-attack damage over large areas are the spatial and temporal nature of red attack on the landscape, and physical limitations due to sun angles and topography. Special attention should be given to image selection, ancillary data requirements including analysis masks and calibration/validation data, image geometry, radiometric normalization, and the iterative determination of EWDI thresholds. Difficulties and possible inconsistencies in setting threshold values are acknowledged and may be mitigated through

the application of a logistic-regression-based mapping approach whereby continuous probabilities of red attack are produced over the area of interest (Wulder et al. 2006c).

Detection and mapping red-attack damage at the tree-level

Information need

Successful mitigation of mountain pine beetle attack relies on accurate detection of infested trees, and on information of the number and location of attacked trees. This detailed information is critical for a range of activities, including sanitation logging, the implementation of silvicultural regimes designed to reduce the susceptibility of host trees, and treatments to directly control beetle populations. In each of these cases, information on the location and health of individual tree crowns is critically important.

Background

Digital satellite remote sensing offers a complementary technology for the detection and mapping of mountain pine beetle red-attack damage with benefits that include the capacity to cover large spatial areas - ensuring a census, rather than a sample, of forest stands (Wulder et al. 2006a). In addition, remotely sensed data can easily be integrated with other spatial data (such as roads, elevation and climate data) (Dial et al. 2003; Tao et al. 2004) and forest inventory data (Wulder et al. 2005). Furthermore, there is a reduction in interpreter subjective bias through the application of automated delineation methods (White et al. 2005), which may increase the consistency and reliability of mapping between different areas or dates (Wulder et al. 2006a).

The advent of high spatial resolution satellite data, since the launch of the IKONOS satellite in 1999, has resulted in an increased capacity to detect these individual trees from space. High spatial resolution remotely sensed data is useful for identifying small disturbances focused over a limited spatial extent and can serve as a surrogate for field-based measurements (Asner and Warner 2003) or validation efforts (Morisette et al. 2003). In addition, airborne digital imagery, such as that obtained by digital cameras sensitive to both the visible and near infrared regions of the spectrum, also provides a capacity to deliver detailed information for individual trees.

Application example

In forest stands infested by mountain pine beetles, Kneppeck and Ahern (1989) compared manually derived counts of red-attack trees from airborne scanner imagery (with a 1.4 m spatial resolution) to counts estimated by manual interpretation of 1:10,000 air photos. Counts of red-attack trees from 1.4 m resolution imagery were higher (136%), while counts from 3.4 m resolution imagery were lower (71%). The results from this study indicate that detailed surveys can also benefit from a multi-stage sampling approach where a small sample of ground counts is used to adjust estimates generated from other data sources.

White et al. (2005) use IKONOS 4-m multispectral data to detect mountain pine beetle red-attack damage. In this study, an unsupervised clustering technique was applied to detect red-attack damage in forest stands with low and moderate levels of attack, and these estimates were then compared to estimates of red-attack damage generated from air photo interpretation. Results indicate that within a one-pixel buffer (4 m) of identified damage pixels, the accuracy of red-attack detection was 70.1% for areas of low infestation (stands with less than 5% of trees damaged) and 92.5% for areas of moderate infestation (stands with between 5% and 20% of trees damaged). Analysis of red-attack trees that were missed in the classification of the IKONOS imagery indicated that detection of red-attack was most effective for larger tree crowns (diameter >1.5 m) that were less than 11 m from other red-attack trees.

Coops et al. (2006) use helicopter GPS measurements of beetle-infested pine trees in north-central British Columbia to indicate areas of attack and non-attack stands on QuickBird 2.4 m multispectral data (blue, green, red, near-infrared). Using a 50-m buffer around each GPS point, the authors tested the ANOVA (Analysis of Variance) separability of each of the four QuickBird spectral bands along with a Normalized Difference Vegetation Index NDVI and red/green spectral ratio (Red-Green Index or RGI) under four classes: sunlit non-attacked crowns, dense red-attack crowns, fader crowns, and shadowed crowns. Based on the results of the ANOVA, spectral thresholds were used to generate a binary map for red attack and non-attack (combining non-attacked crowns with crowns obscured by shadows). The results show that the ratio of the red to green QuickBird spectral bands was the most significant band combination for detecting red-attack beetle damage and the results from QuickBird imagery had good correspondence to both forest health survey data and broader spatial resolution Landsat imagery.

While numerous attempts at detecting damage caused by insects with remotely sensed data have proven successful [see Gimbarzevsky et al. (1992), Roberts et al. (2003), Riel et al. (2004) for more examples than those presented previously], research that utilizes high-spatial-resolution remote sensing data is not as extensive (Bone et al. 2005). This is because forests are complex systems that are highly heterogeneous and per pixel classification or analysis does not sufficiently capture the inter-pixel variance in high-spatial-resolution imagery. As a result of the challenges associated with analyzing high spatial resolution data, new analysis techniques have been developed, including region-growing image analysis using a combination of the shape, size, and spectral data of the regions to classify image data (Chubey et al. 2006; Hay et al. 2005; McKeown 1988), the application of spatial statistics through the use of a variogram (Atkinson et al. 1996), extraction of image textural attributes (Coops and Catling 1997; Johansen and Phinn 2006; Wulder et al. 1998) and image object recognition approaches (Culvenor 2003).

As mentioned previously, ground surveys are typically used to estimate G:R. High-spatial-resolution, remotely sensed data can provide information on tree-level red-attack damage, which in turn can be used for estimating rates of mountain pine beetle population increase (based on changes in red-attack damage levels over time). In a recent study, we estimated average stand-level G:R using a time series of QuickBird multispectral and panchromatic satellite data combined with field data for three forested stands near Merritt, British Columbia, Canada. The approach is summarized in Figure 6. Using a ratio of QuickBird red to green wavelengths as per Coops et al. (2006), the change in RGI (ΔRGI) in successive image pairs was used to estimate red-attack damage in 2004, 2005, and 2006, with true positive accuracies (for red attack) ranging from 89% to 93%. The time series of imagery selected for this study was collected over a range of viewing and illumination conditions and, as a result, different portions the tree crowns are in shadow from one image to the next. This results in variability in the spectral response, which confounds attempts to assess the health of individual trees, although it is possible to determine the health of small groups of trees. To overcome issues associated with differing viewing geometry and illumination angles, which impair tracking of individual trees through time, we generated segments from the QuickBird multispectral data (2.7-m spatial resolution) to identify small groups of trees. These segments then serve as the vehicle for monitoring changes in red-attack damage over time (as assessed using ΔRGI). A local maxima filter was applied to the QuickBird panchromatic data (0.6-m spatial resolution) to estimate stem counts, thereby allowing an indication of the total tree population at risk of attack. Examples of segments, local maxima outputs, and red-attack damage are illustrated in Figure 7. By combining the red-attack damage estimates with the local maxima stem counts, predictions were made of the number of attacked trees in a given year. Backcasting the current year's red-attack damaged trees as the previous year's green attack facilitates the estimation of an average stand G:R. In this study area, the retrospective G:R values closely matched those generated from field surveys. The results of this study indicate that a monitoring program using a time series of high-spatial-resolution remotely sensed data (multispectral and panchromatic) over select sample locations could be used to estimate G:R over large areas, facilitating landscape level management strategies or providing a mechanism for assessing the efficacy of previously implemented strategies.

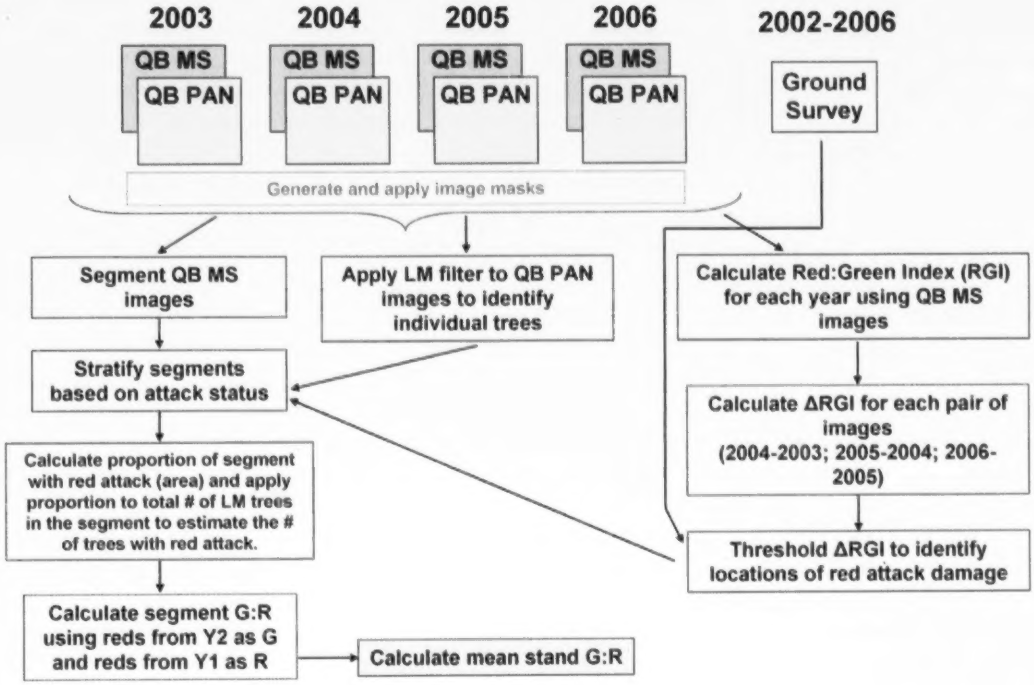

Figure 6. A schematic of how multi-date QuickBird multispectral and panchromatic imagery are used to generate segments, estimate tree counts, and detect red-attack damage; all necessary components required to estimate a green-attack to red-attack ratio (G:R).

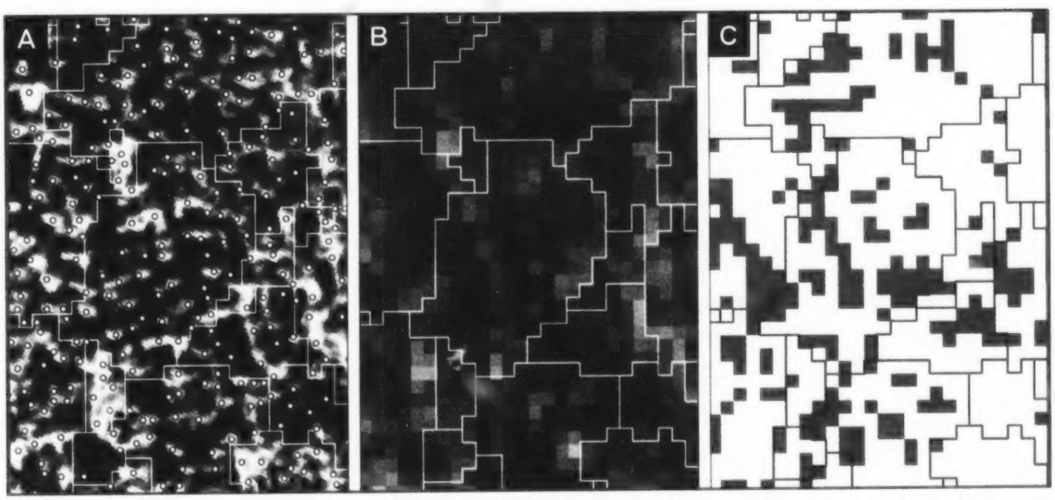

Figure 7. A portion of a study area near Merritt, British Columbia. (A) Segments are used as the vehicle to track changes in red-attack damage over time, while local maxima points (yellow) provide estimates of total tree counts. Shown in the background is the 2003 QuickBird panchromatic imagery (0.6-m spatial resolution). (B) The segments were generated from the 2003 QuickBird multispectral imagery (2.7-m resolution) and are shown here draped over the 2006 QuickBird multispectral imagery. (C) Areas identified in red represent those areas where there were changes between the 2006 and 2005 RGI values (ΔRGI) that were identified as mountain pine beetle red-attack damage (using calibration data of known damage locations).

Conclusion

In this report, we have demonstrated how information needs influence the choice of remotely sensed data and analysis methods. Regardless of whether the scope of the application is over large areas or at the level of individual trees, there are several logistical issues related to data acquisition and processing that must be addressed. In the context of mountain pine beetle red-attack damage, a robust method has been developed for detection and mapping at the landscape level. Using this approach operationally over large areas (e.g., the entire province of British Columbia) presents several additional challenges. At the tree level, red-attack mapping for low and moderate levels of attack has been demonstrated and may provide complementary information for monitoring and mitigation activities, especially when forming a component of a multi-stage, sample-based program. The focus on meeting information needs using remotely sensed data will allow the remote sensing community to support sustainable forest management and to play a role in informing policy makers. While the discussion in this communication has focused on mountain pine beetle infestation, many of the issues, considerations, and decision points are portable and can be considered generic to other purpose-based applications of remote sensing of vegetation.

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